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DESIGN AND VERIFICATION OF CLASSICAL CONTROLLER FOR TRANSFORMER LESS DC-DC BOOST CONVERTER

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ABSTRACT

This article studies on a design and Verification of classical controllers (CC) for Transformer less DC-DC Boost Converter (TDC-DCBC) operated in Continuous Conduction Mode (CCM) for applications wanting a stable power source in I-pad, mobile phones, MP-3 player, lap-top computers, robot interface communication device and solar energy etc.,. Attributable to the ON/OFF characteristics of TDC-DCBC is non-linear in nature and it generates meager dynamic performances and also, unsatisfactory output voltage regulation. With the aim of increase the dynamic performance and output voltage regulation of TDC-DCBC, a CC is designed. In this article proportional integral (PI) controller is taken as one of the CC. The PI controller parameters are arrived from the modeling of TDC-DCBC with help of the state space averaging approach. The performance of the designed converter with PI controller is validated at different operating state by building both matrix laboratory (MATLAB)/simulation link (Simulink). The results are presented to prove the performance designed converter with CC.

KEYWORDS: Transformer less DC-DC boosts converter (TDC-DCBC), Proportional plus Integral (PI) controller, Continuous Conduction Mode (CCM), Classical Controllers (CC), MATLAB/Simulink.

Introduction

In recent days, the DC-DC conversion technology plays a major role in power engineering and drives. These converters are broadly applied in several industrial applications such as discharge lamp for automobile, fuel cell energy conversion systems, and computer hardware circuits. Also, these are widely used for traction motor control in electric automobiles, trolley cars, marine hoists, forklifts trucks, mine haulers and are applied in DC voltage regulators. Owing to they provide high efficiency, and the conversion techniques are developed very rapid [1]. Input power for the DC-DC boost converters are taken from any appropriate DC sources such as DC generators, batteries, solar panels and rectifiers etc.,. The technique that changes one DC voltage to a different DC voltage is called as DC to DC conversion. Commonly, a boost converter is a DC to DC converter with an output voltage more than the input source voltage [2]. However, the transformer less converters topology provides good performance (like efficiency) and other constraints compared to transformer converters topology [3]. There are two important kinds of DC-DC converters namely transformer less (isolated DC-DC converter) and with transformer (non-isolated DC-DC converter) [4]. The traditional type DC-DC boost converter cannot offer high level controlled DC voltage gain for an excessive duty cycle. It may cause in reverse recovery crisis and amplify the rating of all devices. Accordingly, the conversion efficiency is decreased. The main merits of DC-DC boost converter is simple structure and continues input current. At the same time, it has demerit such as when the switch is OFF, high output voltage is impressed on the switch, low voltage transfer gain and more ripples of current and voltage. Therefore, the classical boost topology is not fit for large power application owing to the occurrence of parasitical resistance (free loading). Many types of single switched topologies based on the conventional boost converter had been presented for high step–up voltage gain [5]–[9]. The cascaded boost converter is also competent of offering good voltage gain without problem of high duty cycle [10]. However, the voltage stress of the main switch is equal to the output voltage. Three-level boost converter can double the voltage gain and equally share the voltage stress across the power device over the traditional two-level boost converter, which is more apposite in low-voltage-input to high-voltage-output applications[11]. The three level boost converters reduces the reverse recovery losses of the diodes in addition to increases the overall power efficiency. Yet, the major problem of three-level and cascade converter needs more sets of power devices, magnetic cores and control circuits, which is complex and enhance the circuit complexity and cost [12]. The classic DC-DC converters consist of storage elements of inductors and capacitors. They are large due to the concoction of inductors and capacitors. As per the engineering design aspect, the design of a circuit by only storage element of inductor or capacitor will be the minimum in size. So as to reduce the converter size and increase the power density, third generations of DC-DC converters are developed and they are called switched component converters [13]. They are Switched-Capacitor (SC) DC-DC converters and Switched-Inductor (SI) DC-DC converters. The SC DC-DC converter is an innovative type of

DC-DC conversion technology. While a SC can be integrated into a power IC chip. These types of converter are small in size and have a good power density. Most of the SC converters have little low power transfer efficiency. Various modeling techniques of DC-DC converters has been presented [14]. Among them state space averaging method is best and accurate method. The classical Proportional-Integral (PI) controller for DC-DC converters has been presented [15]. The main function of the controller is used for output voltage and inductor current regulations any topology of DC-DC converter and also, to improve the time/frequency domain specifications. The above problems are solved by designed Transformer less DC-DC Boost Converter (TDC-DCBC) operated in Continuous Conduction Mode (CCM) using Classical PI controller.

Therefore, in this article presents a design of PI controller for TDC-DCBC in CCM. Initially, the modeling of this converter is derived and then, PI controller parameters of it are estimated using Ziegler Nicholas Tuning Method (ZNTM). The performance of the designed model is verified by MATLAB/Simulink software platform at various operating conditions. The main role of PI controller in this article is used to regulate output voltage of this converter.

OPERATION OF DC-DC CONVERTERS

A. Working principle of Traditional DC-DC Boost converter

The DC-DC boost converter operates in two modes due to the existence of the switch. When switch is closed, the inductor stores energy and the capacitor releases energy. When switch is open, the inductor releases energy and the capacitor stores energy. Fig. 1 show the circuit diagram of DC-DC boost converter. From this figure, all the elements in the circuit does not consume energy at ideal condition, there must exist two fundamental conservation laws between the output and the input.

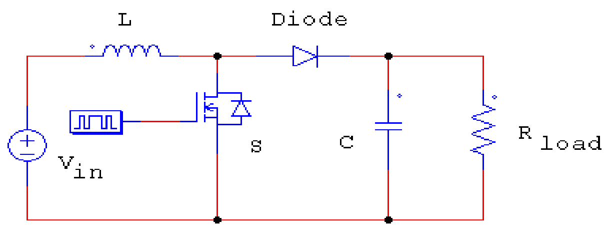


Fig.1. Topology of DC-DC boost converter circuit.

The first law involves the energy balance that needs that the input energy equals the output energy,

Pin =Po => Iin Vin =Io Vo (1)

Where,
Pin-Input power
Pout-Output power
Iin-Input current
Io-Output current
Vin-Input voltage
Vo-Output voltage

The second law is the charge balance that indicates the input charge is equal to output charge. On account of the switch the input current can only provide charge to output side when switch is open, and the time is (1-d)T in one T-period.

Qin=Qo => Iin(1-d)T=IoT (2)

Where,
Qin-Input charge
Qo-Output charge
d-duty cycle
T-Switching time period

Using the two equations we can derive the basic relationship between the input voltage and output voltage.

$$Vo=\frac{Vin}{1-d} \quad (3)$$

"d" is a positive number less than 1. From the relationship, it can see clearly expressed as

Vo>Vin (4)

B. Design of dc-dc Boost Converter

This section is discussed about design formulas of the DC-DC boost converter [16].

Step1. LOAD RESISTANCE

$$\text{Load Resistance} = \frac{Vo}{Io} \quad (5)$$

Where, V0 = Desired output voltage
I0 = Desired output current

Step2. DUTY CYCLE

$$\text{Duty Cycle} = 1-\frac{Vin}{V0} \quad (6)$$

Where Vin =Input voltage
V0 = Desired output voltage

Step3. CAPACITOR

$$\Delta V0 = ESR\left[\frac{I0}{1-d}+\frac{\Delta ILnew}{2}\right] \quad (7)$$

$$C=\frac{I0\times D}{fs\times\Delta V0} \quad (8)$$

Where,
Io = Desired output current
d = Duty cycle
fs = Switching frequency
$\Delta V0$ = Output ripple voltage
ΔIl = Inductor ripple current
ESR =Equivalent series resistance of the capacitor

$$\text{New Ripple Voltage} = \frac{I0\times d}{fs\times C} \quad (9)$$

Table. I Design Specifications of TDC-DCBC

S. No	Parameters	Values
1	Input Voltage(Vin)	5V
2	Input Current(Iin)	4999A
3	Output Voltage(Vout)	21.8V
4	Output Current(Iout)	0.348A
5	Duty Cycle(d)	0.77
6	Load Resistance(R)	63 Ω

7	Inductance(L)	68 µ H
8	Capacitance (C0, C1& C2)	380 mF, 22 µ F
9	Equivalent series Resistance (ESR)	2 Ω

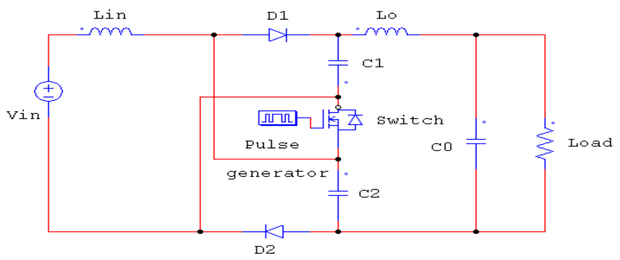
Step4. INDUCTOR

$$L = \frac{Vin*(Vo-Vin)}{\Delta Il*fs*Vo} \quad (10)$$

Where,
ΔIl =10% $of\ Io$
Vin =Input voltage
V0 =Desired output voltage
fs = Switching frequency
ΔIl = Inductor ripple current
Io = Desired output current

Diode: In order to reduce losses, ultra fast recovery diodes can be used. The forward current rating needed is equal to the maximum output current. From the above equations the design parameters are obtained as catalogued in Table I.

NEW HIGH STEP-UP BOOST CONVERTER TOPOLOGY (TDC-DCBC)



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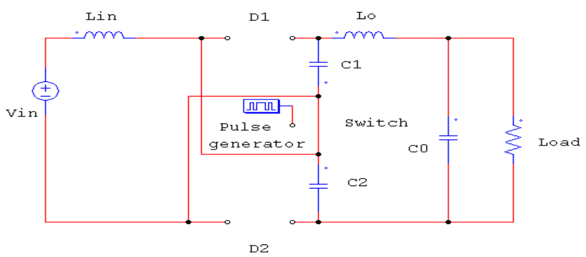

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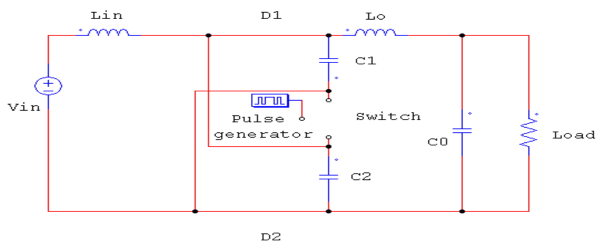


(c)

Fig.2. (a) Power circuit diagram of a new high step-up DC-DC boost converter topology, (b) Equivalent circuit of mode 1 operation, and (c) Equivalent circuit of mode 2 operation.

The step-up switching circuit is connected with the conventional DC-DC boost converter to get the Hybrid type DC-DC boost converter as shown in fig.2 it is also called as TDC-DCBC. It consists of a two capacitors C1& C2, two inductors Lin & Lo with two diodes D1 & D2 and is operated with a switch S. Here capacitor C0 is connected for filtering purpose. The topology diagram of TDC-DCBC as shown in Fig.2(a).

MODE-1: During mode-1 operation, switch S is in ON position, the diodes D1 & D2 are in reverse bias i.e. non-conduction state and the boost inductor Lin is energized form the Vin. The equivalent circuit diagram mode 1 is depicting in Fig. 2 (b).

MODE-2: During mode-2 operation, switch S is in OFF position, the two diodes D1 & D2 are in forward bias i.e. conduction state as shown in the Fig.2 (c), and then, the boost inductor Lin is discharged through the capacitor C0 and to the load (R). Here, the switch S acts as a classical boost converter. It means the switch control the total energy transfer through the inductor Lin. The change of configuration of the switched capacitor is a derivative action of switch (ON/OFF) no control is compulsory on charging and discharging of capacitors C1 & C2. Then, the switched capacitor circuit can operated at its optimal efficiency.

Assuming that the converter is operating in CCM, C1= C2=C and VC1=VC2=VC

The state-space model of this converter is expressed by equations

$$\frac{diL1}{dt} = -\frac{(1-d)}{L1}VC + \frac{E}{L1} \quad (11)$$

$$\frac{diL2}{dt} = \frac{(1-d)}{L1}VC - \frac{1}{L2}V0 \quad (12)$$

$$\frac{dVc}{dt} = \frac{(1-d)}{2C}iL1 - \frac{1+d}{2C}iL2 \quad (13)$$

$$\frac{dV0}{dt} = \frac{1}{C0}iL2 - \frac{1}{RC0}V0 \quad (14)$$

Here, iL1, iL2, VC and V0 are the averaging currents of inductors L1, L2 and the averaging voltages of capacitors C0 & C respectively. E is the input voltage. R is the load resistance of the converter &'d' indicates the control signal of the switch (0, 1).

The system is described by the following set of continuous time state space equations.

$$\dot{X}(t) = AX(t) + BVin)$$
$$Y(t) = CX(t) + DVin) \quad (15)$$

Where x is a state vector, Vin is a source vector, A, B, C, D is the state coefficient matrices. State model of the TDC-DCBC or the high step-up DC-DC boost converter is derived as High power densities are possible only for CCM operation. Diode D

and switch S are always in a complementary state, when S-ON, D-OFF and vice versa. Two modes of operations are possible and its corresponding state equations model of TDC-DCBC is

$$\begin{bmatrix} \frac{diL1}{dt} \\ \frac{diL2}{dt} \\ \frac{dVc}{dt} \\ \frac{dV0}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1-d}{L1} & 0 \\ 0 & 0 & \frac{1+d}{L2} & -\frac{1}{L2} \\ \frac{1-d}{2C} & -\frac{1+d}{2C} & 0 & 0 \\ 0 & \frac{1}{C0} & 0 & -\frac{1}{RC0} \end{bmatrix} \begin{bmatrix} iL1 \\ iL2 \\ VC \\ V0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L1} \\ 0 \\ 0 \\ 0 \end{bmatrix} [Vin] \qquad (16)$$

C = [0 0 0 1], and D = 0.

DESIGN OF CLASSICAL PI CONTROLLER FOR NEW HIGH STEP-UP BOOST CONVERTER TOPOLOGY

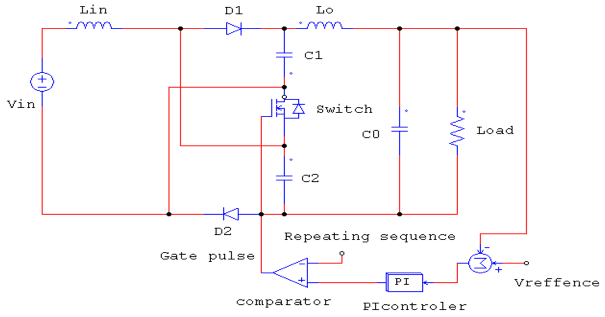


Fig.3. Closed loop operation of high step-up DCBC using classical PI controller.

Fig. 3 shows the complete structure of high step-up DC-DC boost converter topology with classical PI controller. The output voltage of the system is measured and compared with its reference output voltage that gives the error signal. This error signal is processed through the PI controller to generate the control signal. This control signal is compared with the repeating sequence signal to generate the gating pulses, which in- turn regulates the output voltage of the high step-up DCBC or TDC-DCBC. PIC parameters, proportional gain (Kp) and integral times (Ti), are obtained by using Zeigler – Nichols second tuning method. The transfer function (T.F) model of TDC-DCBC is,

$$\text{T.F}=\frac{5s^4+9.988e^4s^3+1.342e^9s^2+1.8e^{11}s+2.293e^{15}}{s^4+0.04177s^3+1.5651e^6s^2+4.105e^4s-1.182\,e^{10}} \qquad (17)$$

The characteristics equation with proportional gain (K) of (17) is expressed as

(5K+ 1) S4 + (0.04177+9.988K) S3 + (1.5651 e6 +1.342 e9K) S2+ (4.105 e4 +1.8 e11 K) S+ (2.293e15-1.182 e10 K) = 0 (18)

The Routh array of equation (18) is

S4: (5K+1) (1.5651e6 +1.342e9K 3.696e8) (2.293e15-1.182e10 K)

S3: (0.04177+9.988K) (4.105e4 +1.8e11 K)

S2: (1.5651e6 +1.342e9K) (2.293e15-1.182e10 K)

S1: (4.105e4 +1.8e11 K)

S0: (2.293e15-1.182e10 K)

From this routh array, the sort of K for stability is, K > 287.911, 0 < K <287.911. Hence, the critical gain Kcr = 287.911. When K=287.911 the imaginary roots as the S1 row is identically 0. The corresponding auxiliary equation is

1950413.692 S2 -2.229e15=0

and their resultant roots ω_n =1174110340 rad/sec and Pcr=2*pi / ω_n =5.35e-9. Later than tuning the controller using this method, the converter reaches expected steady state with few oscillations, where the ultimate gain for stability can be found as Kcr=287.911 and their corresponding ultimate period as Pcr=5.35e-9. Using this Table 2 values of Kp=0.45*Kcr=129.559 and integral time Ti=Pcr/1.2 = 4.458e-7 s are computed.

Table 2. Ziegler Nichols Recipe – Second Method

PID Type	*Kp*	*Ti*	*Td*
P	$0.5K_{cr}$	∞	0
PI	$0.45K_{cr}$	$\frac{P_{cr}}{1.2}$	0
PID	$0.6K_{cr}$	$\frac{P_{cr}}{1.2}$	$\frac{P_{cr}}{8}$

SIMULATION RESULTS and DISCUSSIONS

This section validates the above design, and also discusses performance of the feedback PI controller for the specifications catalogued in Table 1. Fig. 4 indicates the MATLAB/Simulink model of high step-up DCBC with/without controller.

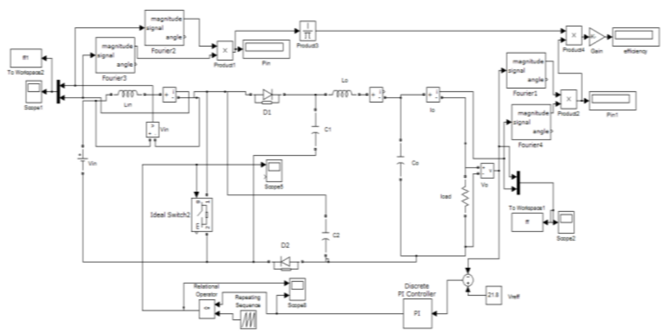
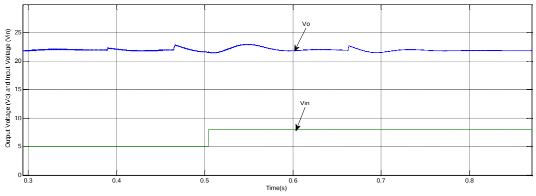


Fig.4 MATLAB/Simulink schematics of the designed system using controller.

Figs. 5 and 6 show the simulated output voltage and input voltage of TDC-DCBC using designed controller in line variations. From the results, it is clearly found that the output voltage of the designed converter has produced less peak overshoots and quick settling time at different input voltage variations.



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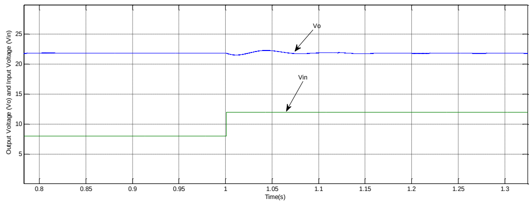

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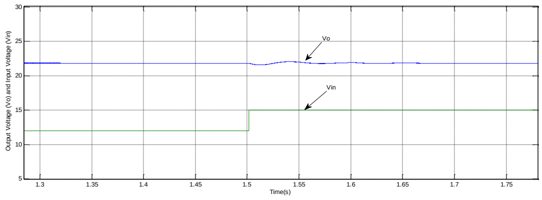
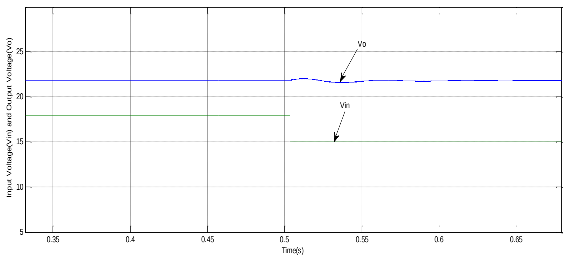


(c)

Fig. 5 Simulated output voltage and input voltage under line variation of TDC-DCBC using classical PI controller, (a) for input voltage change from 5V to 8V, (b) for input voltage change from 8V to 12V, and (c) for input voltage change from 5V to 15V.



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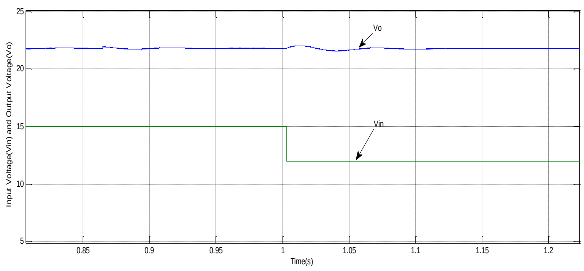

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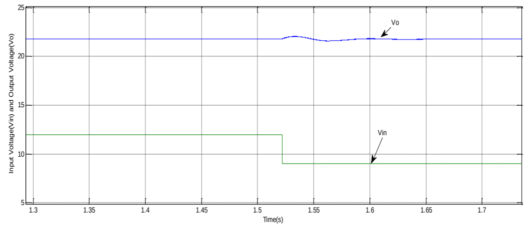

(c)

Fig.6 Simulated output voltage and input voltage under line variations of TDC-DCBC using classical PI controller, (a) for input voltage change from 18V to 15V, (b) for input voltage change from 15V to 12V, and (c) for input voltage change from 12V to 8V.

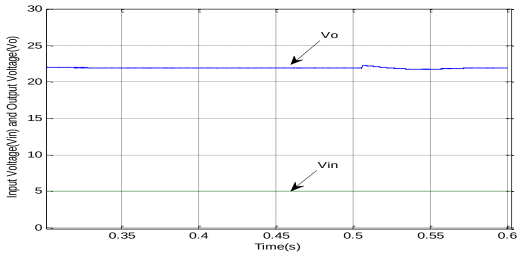

Fig.7 Simulated output voltage and input voltage under circuit capacitor (Co) variations from 380 mF to 500 mF of TDC-DCBC using classical PI controller.

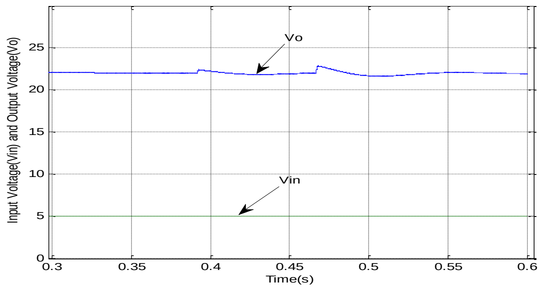

Fig.8 Simulated output voltage and input voltage under circuit inductor (Lo) variations from 68 μ H to 80 μ H of TDC-DCBC using classical PI controller.

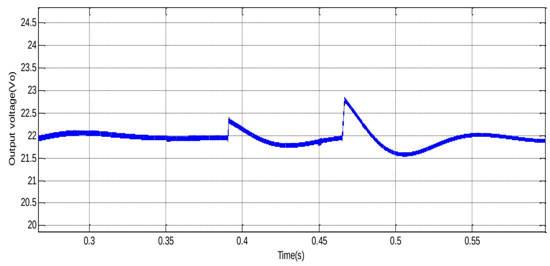

Fig.9 Simulated output voltage of TDC-DCBC in steady state region.

Figs. 7 and 8 show the simulated output voltage and input voltage of TDC-DCBC using designed controller during output capacitor variation from 380 mF to 500 mF and inductor variations from 68 μ H to 80 μ H. It is evident that the designed converter has been maintained the output voltage with small overshoot using PI controller.

Fig.9 show the output voltage of the converter in steady state region using controller. From the results, it is found that the ripple of output voltage is mV range.

CONCLUSION

The TDC-DCBC using PI controller has been demonstrated with MATLAB/Simulink software platform. The designed converter is tested at different operating conditions using PI controller has produced excellent performance. Many simulation results are presented to prove the effectiveness of the TDC-DCBC over the conventional boost converter. Also, the designed converter has produced minimal ripple of the output voltage. Therefore, it is more suitable for constant power supply for LCD display, MP-3 player, medical equipments, and renewable energy source.

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